

Clouds and the Earth's Radiant Energy System (CERES)

Validation Document

Validation of Imager Cloud Optical Properties (Subsystem 4.3)

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VALIDATION OF IMAGER CLOUD OPTICAL PROPERTIES

Abstract

Cloud physical and optical properties determine how clouds affect the radiance and flux fields at the surface, within the atmosphere, and at the top of the atmosphere. In the Cloud Property Retrieval Subsystem (COPRS), CERES analyzes individual pixel radiances to derive the cloud properties that influence the radiation fields. For each pixel, state-of-the-art methods are used to ascertain the temperatures and pressures corresponding to the cloud top, base, and effective radiating center; the phase and effective size of the cloud particles; the cloud optical depth at a wavelength of 0.65 μm ; the cloud emittance at 10.8 μm ; and the cloud liquid or ice water path. An approach for validating these remotely sensed cloud properties is described in this document. The strategy includes both pre-launch and post-launch comparisons of the satellite imager-derived cloud properties with those determined using other methods or datasets. In some cases, the values from the other techniques are more accurate and, therefore, serve as "cloud truth." Simultaneous retrievals from two different satellites provides an estimate of the relative errors in the retrievals and their dependence on angular configuration, climate regime, and surface type. Theoretical calculations are also used to study the sensitivity of the algorithms to various errors in input data and in some of the basic assumptions. Assessments of overall absolute errors are obtained through comparisons of the COPRS products with coincident datasets from field programs and well-instrumented, long-term monitoring sites. The required correlative data for validation include surface and aircraft measurements of the subsystem parameters using lidars, radars, in situ microphysical probes, microwave radiometers, and sunphotometers. Additional sites are required to obtain correlative data representative of additional climate regimes. New field programs with in situ aircraft measurements are needed to enhance and verify the accuracy of the cloud properties derived from surface observations. Successful validation is effected by a stable estimate of the product uncertainties.

4.3.1 INTRODUCTION

4.3.1.1 Measurement and Science Objectives

The CERES Cloud Property Retrieval Subsystem (COPRS; see Minnis et al. 1995, Minnis et al. 1999a,b) employs state-of-the-art methods to derive cloud bulk and microphysical properties from the relevant spectral radiances available from the VIRS, MODIS, and AVHRR imager instruments operating during the EOS era. These parameters must be measured simultaneously with the broadband radiation field to further our understanding of how they affect the exchange of radiation within the atmosphere and how they can be used to improve the interpretation of the measured broadband radiances (Wielicki et al., 1995).

A wide variety of methods are used to derive the COPRS products. The subsystem uses state-of-the-art procedures to arrive at the most accurate values for each parameter. It combines several algorithms to cover as many cases as possible. This document describes the strategy being implemented to insure that the COPRS products are consistent with the standards necessary to meet CERES overall accuracy goals.

4.3.1.2. Missions

This subsystem operates concurrently with the CERES scanners that are on TRMM, Terra, and Aqua. The COPRS was also exercised prior to launch using AVHRR and ERBE scanner data on the NOAA-9 Sun-synchronous satellites. The AVHRR measures radiances at 0.65, 0.86, 3.7, 11, and 12 μm with a nominal resolution of 1 km. The VIRS measures five spectral radiances centered at 0.65, 1.61, 3.7, 11, and 12 μm with a 2-km resolution. MODIS is on the Terra (currently operating) and Aqua (2001 launch) platforms. It has a total of 36 channels with resolutions ranging from 0.25 to 1 km. The COPRS will primarily use MODIS data taken at 0.67, 1.61, 2.12, 3.73, 8.55, 11, and 12 μm with all pixels averaged to a common resolution of 1 km.

4.3.1.3 Science Data Products

The COPRS is applied to each imager pixel that has been identified as cloudy by previous subsystems. COPRS determines the phase, effective particle size, optical depth, emittance, non-vapor water path, radiating temperature, pressure, altitude, and thickness (and cloud base) of the cloud within a given CERES pixel. These imager-pixel cloud properties are used in a later subsystem to determine an average set of cloud properties for each CERES scanner pixel (~25 km x 25 km).

4.3.2 VALIDATION CRITERIA

It is assumed that radiances used in COPRS have already been validated (section 4.1). Therefore, this validation plan only encompasses higher order products. Cloud thickness, pressure, height, and radiating temperature are COPRS products, so the validation approaches discussed in section 4.2 apply to those four COPRS parameters. The verification strategy discussed here will primarily be directed to cloud phase P , effective droplet radius r or effective ice crystal diameter D , optical depth τ , emittance ϵ , and water path WP . Determination of the uncertainties in each property will be made for both daylight and nocturnal conditions.

4.3.2.1 Overall Approach

The validations will operate with two empirical phases, pre-launch and post-launch, and an ongoing theoretical phase. The empirical phases refer to validation techniques that compare results derived from measurements. These efforts also include consistency studies that use multi-angle satellite or satellite/aircraft views. The theoretical phase refers to sensitivity and limitation studies performed using radiative transfer calculations and retrievals of cloud properties from simulated datasets.

This validation strategy attempts to ascertain to what degree the COPRS products meet the CERES accuracy goals. Table 4.3-1 summarizes the state-of-the-art and desired accuracy goals for COPRS. The values in this table are optimistic estimates based on published reports, theoretical studies, and examination of selected available datasets. These numbers are realistic for situations that currently can be resolved with existing techniques. They do not apply to conditions that resist analysis using state-of-the-art satellite remote sensing methods. For example, during the night and near-terminator conditions, clouds become thermally black for $\tau > 8$ in the infrared wavelengths used to retrieve cloud properties at those times. Thus, it is not possible to determine any of the properties except for τ and phase to the levels of accuracy in the table. Even the phase will be suspect for cloud temperatures T_c between 273 and 233K. Similarly, these numbers assume that only a single-layer cloud is observed. If multiple cloud layers coexist in a single pixel, the accuracy of the retrieval will be compromised significantly.

Given such extreme limitations, it is useful to reiterate the scientific use of these products within CERES. The cloud properties will be related to radiative fluxes at the surface, within the atmosphere, and at the top

of the atmosphere. Shortwave (SW) irradiance is more sensitive to τ , r , P , and WP than longwave (LW) flux. For example, if a cloud is thermally black, the effect on the LW is essentially the same for $\tau = 10$ as it is for $\tau = 100$, or for $r = 4 \mu\text{m}$ as it is for $r = 20 \mu\text{m}$. However, the transmittance or reflectance of a cloud to SW radiation will be substantially different for those different cloud properties. Except for the effect of cloud-base height, the optical depth limitation at night will have minimal impact on the scientific use of the COPRS for radiative flux determination.

Remote sensing of most of the parameters (e.g., r , WP , P) listed in Table 4.3-1 is a relatively new activity. On the other hand, the determination of some of these parameters at the satellite pixel scale using other techniques is also limited. This limitation may yield a validation reference that is nearly as uncertain as the remote sensing value. These constraints are discussed further in the next section. Because of these limitations, the wide variety of cloud conditions, and environment, validation of these cloud properties is a difficult problem. By approaching the validation process from several avenues and seeking consistency between the various methods, it is expected that the resulting estimates of uncertainty in each parameter will be reliable and defensible.

TABLE 4.3-1. COPRS accuracy summary for single-layer clouds only

Parameter	Current Accuracy		CERES Accuracy	
	Daytime	Night	Day	Night
Phase (%)	20%	40%	10%	20%
$r / D (\mu\text{m})$	25%	50%	15%	25%
	25%	50%	25%	35%
	5%	15%	5%	5%
Liquid WP (gm-2)	35%	70%	25%	35%
Ice WP (gm-2)	50%	100%	25%	35%
z	50 hPa	100 hPa	25 hPa	50 hPa

4.3.2.2 Sampling requirements and trade-offs

Many factors affect the retrievals of cloud microphysical properties. Among the more important variables are the viewing and illumination angles, clear-sky radiances and their uncertainties, temperature profiles, cloud-cell size and spacing (or degree of plane "parallelness"), horizontal and vertical inhomogeneities, and the parameterizations used in the algorithms. Theoretical studies can be used to estimate the potential errors arising from each of these factors and from their combined impact. However, the empirical approaches are critical for determining the magnitude and sign of the errors in real clouds. Both types of analysis are essential to both quantifying and understanding the errors in the COPRS products.

a) Visual assessment

The first process for evaluating the quality of the resultant cloud properties is through visual examination of the results. By viewing parameter values in color coded images in formats similar to the original imagery, it is possible to quickly assess whether gross errors are occurring in one or more parts of the algorithm. The capability to view the output and input parameters is a critical component of any validation approach and, because it is the most often used method, constitutes a type of quality control for the output products. It is not possible to visually examine all parameters for all scenes over the entire Earth, therefore, a limited number of cloud validation regions was selected to represent the various cloud climate regimes (see Table 2, Minnis et al. 2000). The CERES Cloud Working Group will use detailed pixel-level output from satellite swaths taken over these regions to perform the visual assessment of the cloud products. Non-physical discontinuities and questionable values will be examined together with the input data to determine the source of the apparent errors. In that manner, it will be possible to correct most deficiencies in the algorithms. It is assumed that most of the algorithmic errors can be minimized everywhere by finding and correcting problems in the cloud validation regions.

b) Consistency studies

A relative measure of the uncertainties in a given parameter can be obtained by deriving the quantity from two simultaneous compatible remote sensing datasets. Such simultaneity may be achieved using combinations of satellites such as GOES-8 and AVHRR or GOES-8 and GOES-9 in pre-launch studies. After launch, the VIRS and GOES, VIRS and MODIS, or VIRS and AVHRR can be used together. Combined aircraft and satellite data can also be used for the same purposes if the scale differences are taken into account. Or multiple passes over the same scene at different angles by the same aircraft can serve the same purpose. Both multi-angle and equal angle datasets should be used. The latter provide a baseline estimate of the differences due to the instrument characteristics. These types of studies are extremely useful for testing the various assumptions and models that are used in the various retrieval methods (e.g., Minnis et al., 1993). For example, P , ρ , and D or r should be the same regardless of the viewing angle. The rms differences in these quantities can provide an estimate of the relative error and an overall assessment of the reliability of a given part of the COPRS. Bias errors must be determined using the data intercomparisons described earlier. Angular consistency analyses should also be performed over areas with the in situ and active sensors to improve provide a more complete evaluation of the retrieval errors.

Satellite consistency studies can be implemented without field experiments and can provide a large statistical database over a variety of surfaces, climates, and times of day. However, they require considerable investment in data acquisition, algorithm preparation, intercalibration, and spatial and temporal matching. Nevertheless, they are essential to obtain the types of statistics needed to establish firm uncertainty estimates of the COPRS products.

Long-term averages of the angular dependence of a particular parameter also provide a measure of its validity. Ideally, a particular parameter should not vary, on average, with viewing and illumination angles

assuming that it has been sampled randomly and sufficiently. Some angular variation is expected in each property, however, because relatively simple models are used to interpret emittance and reflectance from rather complex geometrical structures. Determination of the angular variations and the error relative to in situ or active remote sensing reference data may provide a means for minimizing angular variation in future retrievals or in archived datasets.

To ensure that the derived cloud properties are reasonable, the mean values should also be similar to climatologies derived from other sources. Thus, data from other satellites, like the International Satellite Cloud Climatology Project (ISCCP, Rossow and Schiffer 1999), should be considered for comparison as a measure of the reasonableness of the results.

c) Cloud truth comparisons

Comparisons with cloud truth data constitute the primary technique for establishing an "absolute" accuracy measure. There are many factors that must be considered in any comparison of satellite data with ground-based or aircraft measurements. The most important aspect is the absolute accuracy and precision of the "truth" values. Another primary factor is matching of the truth set with the satellite pixels. Serious scale differences can exist between the pixel and correlative data. For example, a ground-based radar measures only a linear sample of the clouds having a width of only a few tens of meters. The cloud sample is an advected quantity that may change with time. The satellite pixels are taken nearly instantaneously and integrate the effects of clouds over an area that is a few orders of magnitude greater than the radar area. Similarly, the aircraft only samples a small linear portion at one or a few levels within the cloud volume. Therefore, the comparisons with the satellite data must be carefully executed using various statistical approaches.

Some of the scale problems can be minimized using high-resolution remote sensors, such as the MAS, on aircraft and satellites (e.g., Landsat). These radiometers yield pixel sizes that are comparable to those of other instruments. Retrievals can be performed on the small pixels and compared directly to coincident in situ and active remote sensing (e.g., radar) determinations of the same parameter. The small aircraft pixels, however, may not be representative of what the satellite views because of differences in scale and viewing conditions. To alleviate some of that discrepancy, radiances and/or retrievals from individual pixels can be integrated to approximate the satellite view. Retrievals from the corresponding satellite data or from the averaged aircraft radiances can then be compared to the mean aircraft-derived properties for a given view (e.g., Heck et al. 1993). The overall uncertainty then is a combination of the aircraft-reference difference and the satellite-aircraft difference. Included in the former error is the inherent uncertainty in the reference data (in situ, active sensor).

Another approach is to use in situ data to verify or tune a radar or lidar retrieval of the vertical structure of cloud particle size, phase, and water content (e.g. Intrieri et al. 1995; Matrosov et al. 1995; Dong et al. 1997; Mace et al. 1998). Vertical and horizontal integration of these quantities provides estimates of τ , D , P , and IWP comparable to the satellite retrievals. Here again, small-scale in situ data are used to establish the accuracy of a somewhat lower resolution sensor that, in turn, becomes the "truth" source for the satellite data. The radar or lidar data can then be analyzed over significant time periods for a variety of background surfaces and climate regimes. The quantities from the active sensor can be averaged over time intervals that correspond to a certain number of satellite pixels. Radars or lidars at the surface or on aircraft can be used to establish cloud base heights or cloud thickness for similar comparisons with the satellite retrievals (e.g., Uttal et al., 1995). Cloud-base heights can also be accurately determined using ceilometer measurements for clouds below 4 km (e.g., Miller and Albrecht, 1995).

Uplooking microwave radiometers provide a validation source for liquid water path LWP (e.g., Minnis et al., 1992; Han et al., 1995). The approach for validation would be very similar to the radar-satellite comparison. Downlooking microwave instruments can also be used to determine cloud LWP over the

ocean providing a large-area validation reference. There are several techniques available for interpreting these data (e.g., Petty and Katsaros, 1990; Curry et al., 1990; Lin and Rossow, 1996) that have various levels of uncertainty depending on the clouds. The various microwave measurements should be valuable for verifying both LWP and P in a variety of conditions.

Cloud optical depth can also be validated, to some extent, using sun photometers, lidars, and narrow-band flux radiometers at the surface. The first two instruments are most useful for determining optical depths for $\tau < 5$ (Shiobara et al., 1996; Wylie et al., 1995), while the last one may be more applicable to larger optical depths (Min and Harrison 1996). The approach for these instruments is similar to that used for the radars. Emittance and optical depth for thin clouds can be determined from radiance measurements from ground-based and airborne infrared radiometers or interferometers when used in conjunction with lidar and radiosonde data (e.g., Ackerman et al. 1995; Collard et al. 1995). Such values are reliable for single-layer clouds and can serve as sources for emittance validations. Similarly, lidar and radar data can be used with radiosonde data directly to determine effective cloud emittance for thin clouds.

Direct comparisons of in situ data with retrieved properties are important but, because of their difficulty, are extremely limited. For example, Platnick and Valero (1994) and Nakajima and Nakajima (1995) were only able to compare their AVHRR retrievals of r to one set of microphysical data for the entire ASTEX period although many microphysical measurements were taken. Matching the time and location of the satellite overpasses with the aircraft measurements is generally secondary to the other experiment goals. Additionally, the aircraft can only fly at one level making the comparisons even more limited (e.g., Nakajima and Nakajima, 1995; Young et al. 1998). Ou et al. (1995) were able to eliminate the vertical distribution problem by using microphysical data taken by a balloon-borne instrument that passed through cirrus clouds. That type of validation, although very accurate, is limited to a few satellite pixels, is labor intensive, and provides a minimal statistical base. Despite their limitations, in situ measurements should be continued with the main priority of verifying other high-resolution techniques such as the radar-radiometer methods (e.g., Matrosov et al., 1992) that can provide much more data over longer time periods. Secondly, the in situ data should be used, in the absence of the other methods, to directly assess the uncertainties in the satellite retrievals of r , D , WP , and τ .

d) Sensitivity studies

Cloud scenes are observed at various angles at different times of day. The dual satellite approaches can only yield relative errors and will only sample a few angular conditions. Therefore, it is essential to theoretically examine the effects of variable viewing and illumination conditions on the COPRS parameters over a full range of cloud types and background conditions. Radiative transfer calculations should also be used in simulations to estimate parameter errors due to uncertainties in the input radiances and correlative data. Because clouds are not often plane parallel sheets, theoretical studies using advanced radiative transfer models should be performed to evaluate the effects of three-dimensional inhomogeneities in the various cloud properties on the plane-parallel model retrievals. Such studies may lead to the design of techniques to empirically correct the retrieved parameters.

4.3.2.3 Measures of Success

Successful validation of all of the COPRS products is completed when the uncertainties have been determined both theoretically and empirically over all major background and climate types for both multi-layer and single-layer clouds for the full range of applicable viewing angles at all times of day. This effort should be carried out in steps to successfully validate the retrievals for a few of the more important conditions. Thus, the validation efforts should concentrate on a few major climate regimes and backgrounds. For example, convective clouds and cirrus dominate a significant portion of the tropics, low stratiform and scattered cumulus exist over large portions of the marine subtropics, highly variable storm systems prevail

over the midlatitudes, and a wide variety of ice and water clouds occur over the cold bright backgrounds of the polar regions. It is suggested that these regimes, which have already received some scrutiny, be the focus of the initial validation efforts.

When stable statistical measures of uncertainty are achieved from theoretical and empirical efforts in each climate regime, it will be possible to claim the validation as a success. Stable statistics refer to rms and bias errors, that, when averaged with previous estimates, do not substantially change the overall uncertainty in a given quantity. Ideally, the uncertainties should be developed for the various factors noted in the beginning of section 4.3.2.2 to maintain statistical independence of the data used to assess the overall error for a given climate regime. This approach is encouraged but may not be realistic for all of the variables.

Another measure of successful validation will be pre- and post-launch consistency in the variable values and in the multi-satellite intercomparisons. Agreement between the theoretical and empirical uncertainty estimates may also constitute a successful validation because it indicates a relatively complete understanding of the physical processes involved in the retrievals

4.3.3 PRE-ANDPOST-LAUNCHALGORITHMTESTINGANDDEVELOPMENT

During the pre-launch phase many of the algorithms were tested by applying them to satellite radiance datasets taken during field programs or coincidentally with other correlative data. The studies used NOAA-9/14 Advanced Very High Resolution Radiometer (AVHRR,) data (e.g., Minnis et al. 1997; Young et al 1998; Dong et al. 2000a), combined Meteosat and Special Sensor Microwave/ Imager (SSM/I) data (Lin et al. 1998), ATSR-2 (Dong et al. 2000a) and GOES-8 (Mace et al. 1998; Dong et al. 1998a, b; Valero et al. 2000). Other data taken prior to the December 1997 operation of VIRS and the March 2000 operation of MODIS on Terra can still be used for testing the alogrithms. Other satellite and aircraft radiances taken after the beginning of the Terra MODIS operations and before the launch of the Aqua (May 2001) can also be considered as either pre- or post-launch data. Radiances measured by the ER-2 MAS, AVIRIS, and the ARM/UAV MPIR can be used as satellite surrogates. All or part of the COPRS algorithms will be or have been applied to these datasets to determine one or more of the considered parameters during various experiments.

A significant number of experiments were conducted during the pre-launch phase and can provide some correlative data at some level of completeness. These experiments are divided into various climate regimes. Tropical clouds can be examined using data from TOGA/COARE, CEPEX, MCTEX, INDOEX, ARM/TWP IOPs, the 1996 cruise of the ship *Discoverer*, STERAO-B, and SCAR-B. Midlatitude and subtropical continental clouds are the subjects of FIRE-I Cirrus, ICE, FIRE-II, BOREAS, FRIZZLE, RACE, PSUCS, WISP, Arizona 1995, SUCCESS/FIRE, SCAR-C, ARM/SGP IOPs, INCA, and ARM/UAV. Subtropical and midlatitude marine clouds are the foci of FIRE-I Stratocumulus, ASTEX, CASP, NARE, EUCREX'94, ACE1, FASTEX, MAST, and ACE2. ARMCAS, SHEBA, FIRE/ACE, and ARM/NSA IOPs are devoted to measurements of polar clouds. The meanings of the above acronyms are listed in section 4.3.8.

Extensive aircraft measurements are part of most of those field campaigns. The cloud truth aircraft data comprise in situ measurements of cloud particle number density, phase, size, and shape; cloud water content; and, through vertical integration, optical depth, water path, and effective particle size. The last three parameters are directly comparable to the satellite- or radar-derived properties if properly averaged. Surface data from these experiments include measurements taken by uplooking radar and radiometer systems, sun photometers, interferometers, narrowband infrared radiometers, shadowband radiometers, microwave radiometers, and depolarization lidars. The radar/radiometer systems can be used to derive

vertical profiles of cloud phase, effective particle size, and water path. Integration and averaging of these profiles yields values comparable to the COPRS output. Sun photometer and shadowband radiometer data can be analyzed to determine cloud optical depths during the daytime. The accuracy of these results decreases with increasing optical depth. Interferometers and narrowband radiometers are valuable for estimating the spectral emittance of non-black clouds. Presumably, the surface-derived emittances are comparable to their COPRS counterparts. Cloud liquid water path and the presence of cloud liquid water can be determined from passive microwave radiometer measurements. Cloud phase can be profiled for thinner clouds using depolarization lidar data. Cloud liquid water path can also be determined over ocean areas using SSM/I microwave radiometer data.

4.3.3.1 Initial post-launch validation

Examples of some of the initial validation efforts following the launch of VIRS on TRMM are given here to demonstrate the types of analyses that are conducted as the validation effort continues.

a) Visual assessment

Figure 1 shows a set of cloud properties derived from the preliminary CERES cloud algorithm for VIRS data taken off the coast of Peru at 1900 UTC, 12 June 1998. The upper right-hand image is a 3-channel pseudo-color overlay using visible reflectance for red, 1.6- μm reflectance for green, and reversed-scale 11- μm brightness temperature for blue. This combination of colors facilitates recognition of different cloud and surface types in a single image. The yellowish clouds are typically low clouds, while the pinkish clouds are usually ice clouds. The white clouds are generally thick midlevel or high clouds. The phase determination by CERES is very consistent with the appearance of the imagery. The derived optical depths also tend to follow the brightness of image. Although there do not appear to be any artifacts such as unexpected discontinuities or extreme values in this particular set of parameters, such images are used to detect such anomalies or obvious errors. They have been extremely useful for detecting problems in either the input data or in the algorithms.

When obvious discrepancies between the imagery and parameter values are detected, the case can be more thoroughly examined using images of the input parameters, including individual spectral images, differences between the observed and expected clear-sky values, and other variables that may help determine why the discrepancies or artifacts occurred. The code or input values may then be modified to minimize the discrepancy. Whenever the algorithm or input values are changed, results from other scenes are examined to ensure that the alteration did not adversely affect them. Other problems that can be detected through visual inspection of instantaneous results include day-to-night changes in the derived cloud properties, dramatic changes in properties over a given area from examination of two successive overpasses, and significant differences in the properties at the interface between two surface types (e.g., coastline). If the code cannot be altered to eliminate any of the identified problems, then the type of problem encountered and an estimate of its frequency are included, as part of the validation process, in the CERES Data Quality Summary for the relevant subsystem, so that users of the results will be aware of any recognized errors. Such imagery is produced for all of the cloud validation regions for day, night, and twilight overpasses to evaluate all parts of the algorithm.

b) Consistency studies

The angular dependencies of the mean derived cloud particle sizes for one month of VIRS data are plotted in Figure 2 for the solar zenith (SZ) and viewing zenith (VZ) angles. For this particular datasets, the mean effective radius first increases with SZ over ocean surfaces, then rapidly decreases for $\text{SZ} > 60^\circ$. The effective radius tends to decrease slightly with SZ over land. Sampling over deserts is too sparse to determine the true variation. Except for deserts, D tends to decrease with SZ. In all cases, it appears that

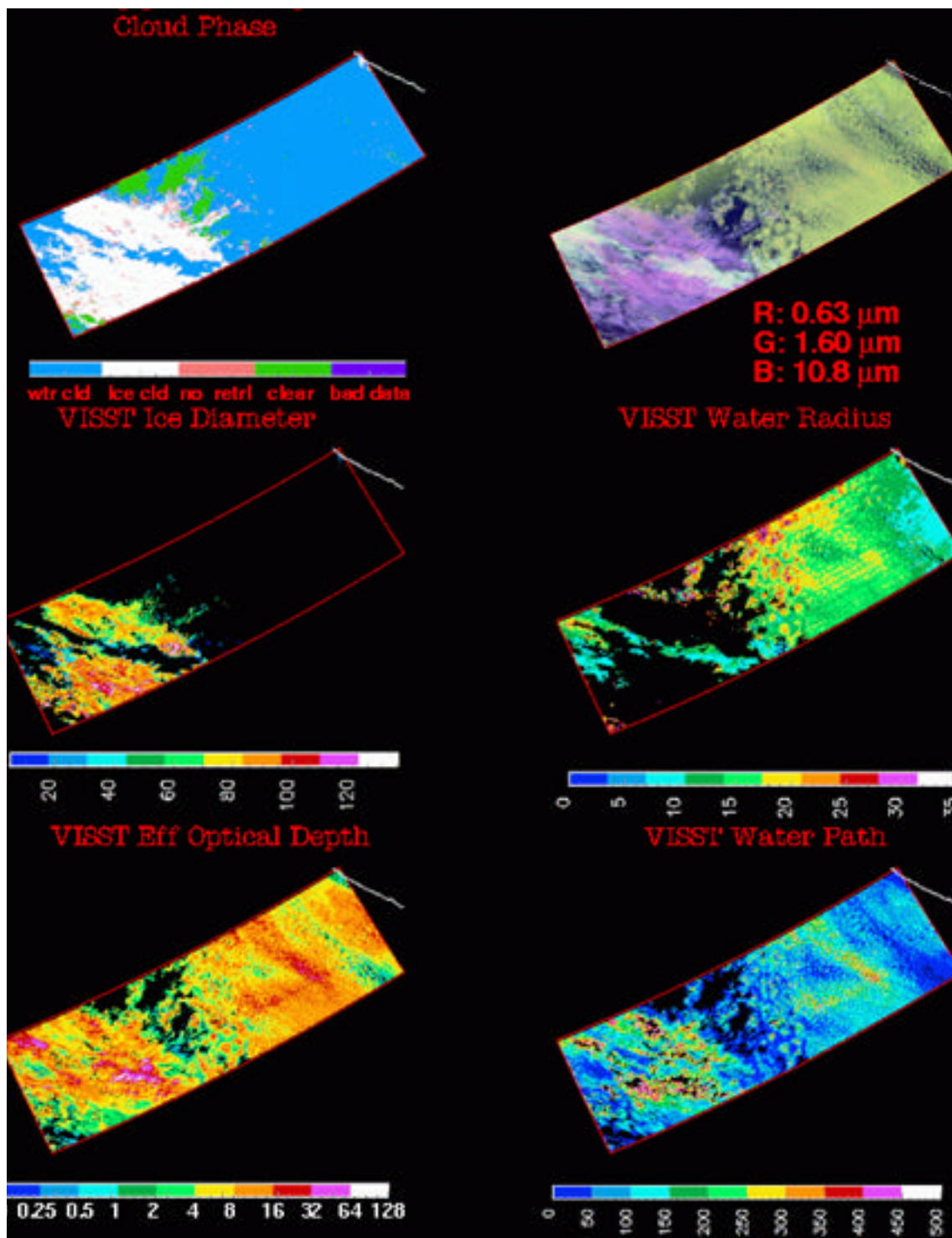


Figure 1. Example of imagery used to visually assess the CERES cloud algorithm results. Data taken off coast of Peru at 1900 UTC, 12 June 1998 by VIRS. Pseudocolor image shown in upper right. Phase indicated by colors: clear/green, ice cloud/white, water cloud/blue, no retrievals/red. Water radius and ice diameter is given in μm . Water path is in gm^{-2} .

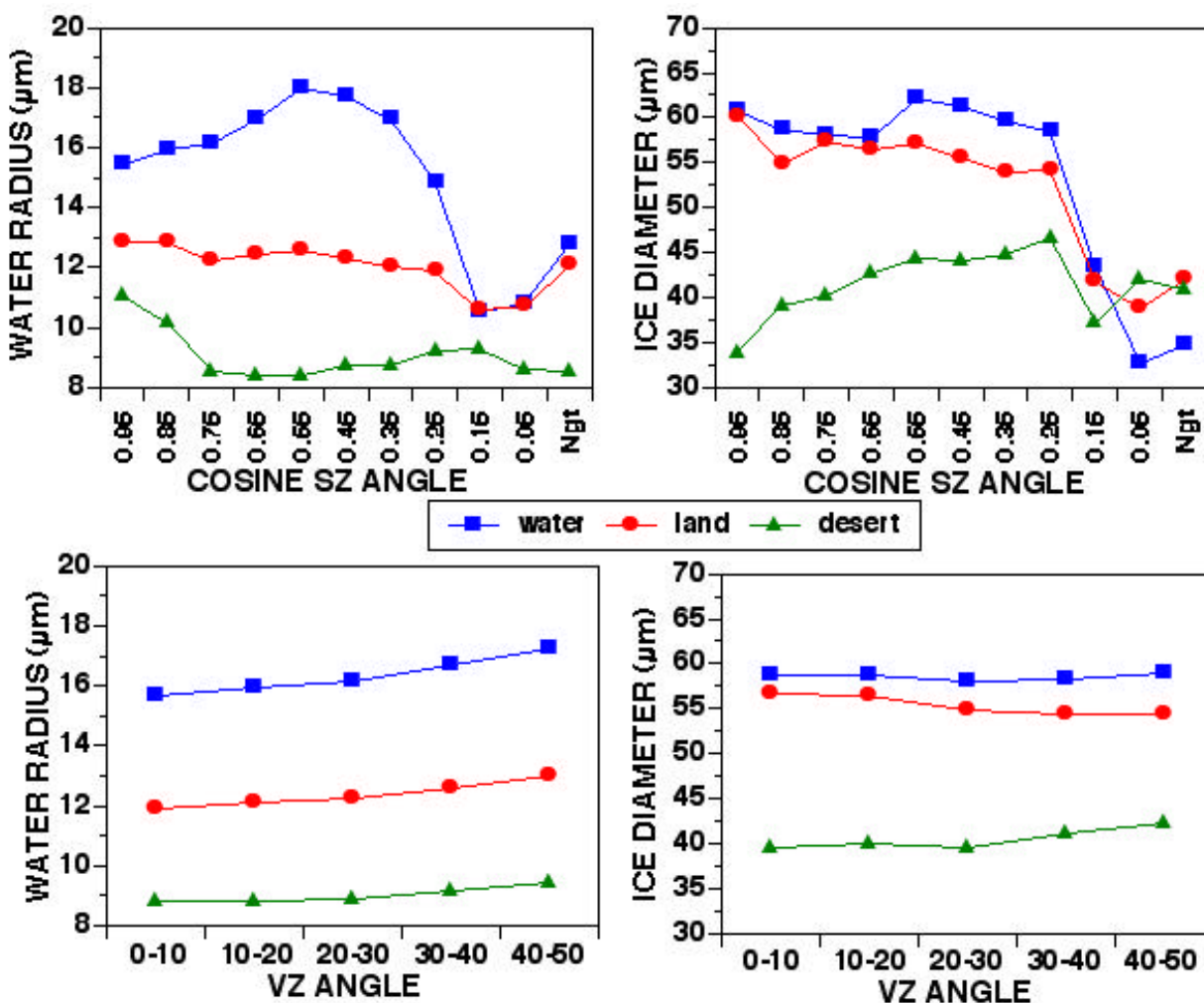


Figure 2. Angular variation of mean effective cloud particle sizes derived from July 1998 VIRS data between 37°N and 37°S using a preliminary CERES cloud retrieval algorithm. SZ is solar zenith and VZ is viewing zenith. All angles given in degrees.

r increases with VZ, while D remains relatively independent of VZ. Similar analyses show some systematic variations of r and D with relative azimuth angle and of τ and, hence, WP on the various angles. The angular variations of these parameters in the initial results may arise from a variety of sources such as sampling patterns, broken cloud effects, or algorithmic errors resulting from inadequate parameterizations or approximations. Much additional analysis and averaging over other time periods and categories are required to sort out the causes of these dependencies. The CERES Cloud Working Group will continue using this validation technique throughout the life of the project. Eventually, some of the variations may be eliminated by adjustments to the algorithms or, perhaps, by proper categorization. Remaining dependencies, like those due to broken cloud effects, may need to be corrected after archival by normalizing to the angles that are most suitable for giving the most accurate results. Any such optimal angles will need to be determined through the process of ground or cloud truth validation.

Comparisons with previous estimates of the same quantities derived from other datasets are also means for determining the reasonableness of the results and for detecting problems in the algorithms. Figure 3 shows an example of monthly mean cloud effective droplet sizes determined from a preliminary

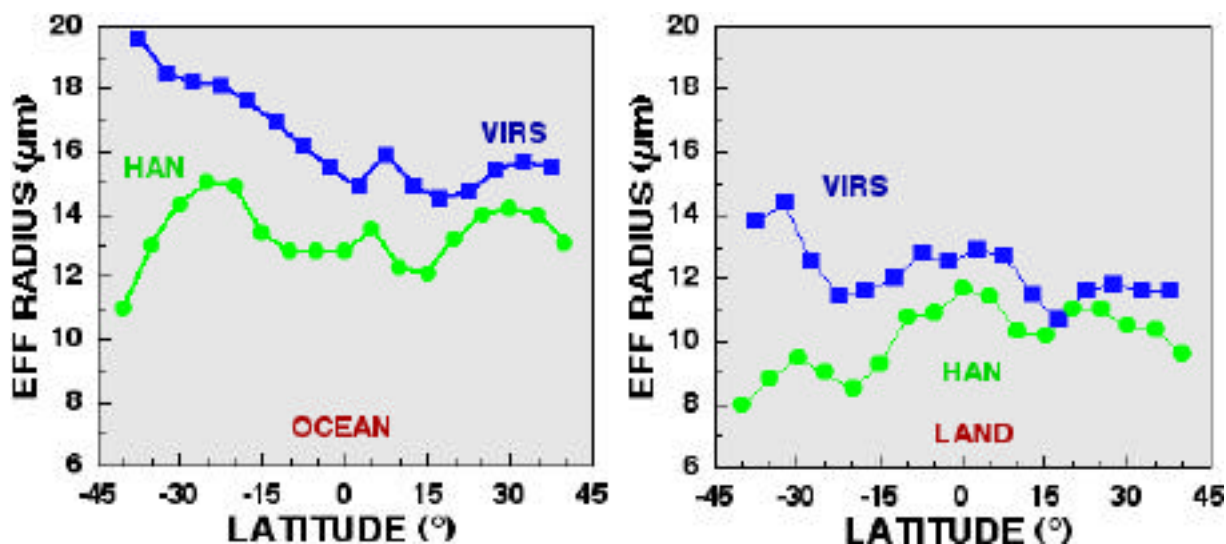


Figure 3. Comparison of zonal mean July effective cloud droplet radii derived from 1987 NOAA-9 AVHRR (HAN) and 1998 TRMM VIRS data. The AVHRR values are only for clouds with $\tau > 3$ and temperatures greater than 273 K. The VIRS results are for all observed water clouds using a preliminary CERES algorithm.

CERES algorithm for July 1998 VIRS data and from July 1987 NOAA-9 AVHRR data by Han et al. (1994) for the selection criteria noted in the caption. This initial plot does not compare the exact same quantities but provides for an initial assessment of the results. The CERES radii are consistent with, but biased relative to the HAN results in the northern hemisphere, but divergent with the HAN results in the southern hemisphere. Such discrepancies require explanation that is developed as part of the validation process. Differences in the selection criteria or shortcomings in the CERES algorithm may be the cause or angular dependencies like those seen in Figure 2 for r with SZ may be manifest in the SZ variation with latitude for the AVHRR. By careful analysis of the results, it should be possible to determine the reasons for differences like those in Figure 3 and perhaps improve the CERES algorithms. CERES results will also be compared with several other climatological datasets such as the WP averages derived from satellite microwave data by Greenwald et al (1987) and ISCCP, to further understand the accuracy of the results. The CERES Cloud Working Group will be carrying out many of these comparisons using published datasets.

c) Cloud truth comparisons

Most of the visual inspection and consistency checks provide only qualitative or relative assessments of accuracy and are valuable as first order validations. Only comparisons with a true reference dataset can provide an absolute accuracy estimation. Figure 4 shows a comparison of preliminary CERES results and cloud properties derived from measurements by instruments based at the ARM/SGP site in Oklahoma during 1998. This example demonstrates the potential for this type of comparison for providing accuracy values for the CERES cloud microphysical products. The mean and standard deviation of both datasets are shown in the upper half of the figure. The VIRS statistics are derived from all pixels within a 30-km x 30-km box centered on the site, while the surface values are based on the data taken during a 30-min period centered on the satellite overpass. The satellite yields a spatial average and the surface sensors provide a time sample. It is assumed that these two values are equivalent. The plots in the upper half of Figure 4 show that the two values for each sample are within one standard deviation of each other providing a clear

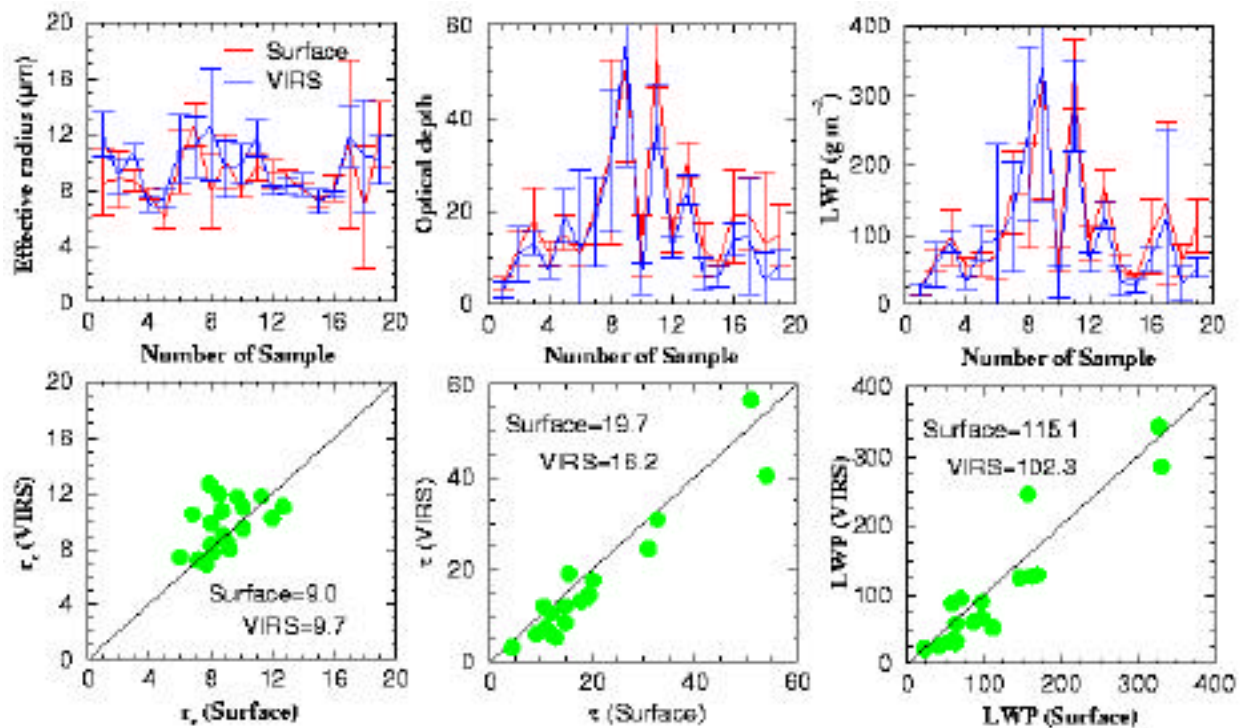


Figure 4. Comparison of daytime stratus cloud properties over the ARM Central Facility derived from simultaneous VIRS and surface-based instrument data for January - July 1998. Preliminary CERES algorithms used to analyze VIRS pixels in a 30-km x 30-km box centered on the site. Method of Dong et al. (1997) was applied to radar, microwave radiometer, and SW radiometer data at ARM site.

picture of consistency between the two datasets. The lower half compares the mean values and shows that r from VIRS is slightly larger than that from the surface, while τ is smaller than its surface counterpart resulting a relative underestimate of WP. This results indicates for this preliminary dataset, that the mean values meet the accuracy limits in Table 1, but are biased. A similar comparison was performed for single-layer thin cirrus clouds that showed that the VIRS optical depths were slightly larger than the surface-based result. Only three data points were found for the cirrus for the 8-month period. These initial validation results are encouraging but provide only a partial assessment. Only 19 stratus and three cirrus daytime samples were found for the 8-month period. It is clear that a long time series of data like those from Dong et al. (2000b) are needed to obtain the necessary number of validation samples for a single cloud type in one climatological regime. Comparisons of results derived from nocturnal and twilight data are also necessary to complete the validation for this single regime. The CERES Cloud Working Group and EOS Validation teams are continuing to evaluate all of the CERES cloud products with independent cloud truth datasets from both in situ and surface-based remote sensors over the ARM sites and for relevant field experiments. Such efforts, however, are currently limited to only a few cloud types (single layer, overcast) and climatological regimes (e.g, only 3 out of 30 selected cloud validation regions).

d) Sensitivity studies

Although few theoretical studies have focused on CERES retrievals per se, a variety of analyses have been conducted that have relevance to COPRS, especially with respect to the determination of cirrus optical depth or ice water path from reflectance data. Through its effects on scattering phase function, single-

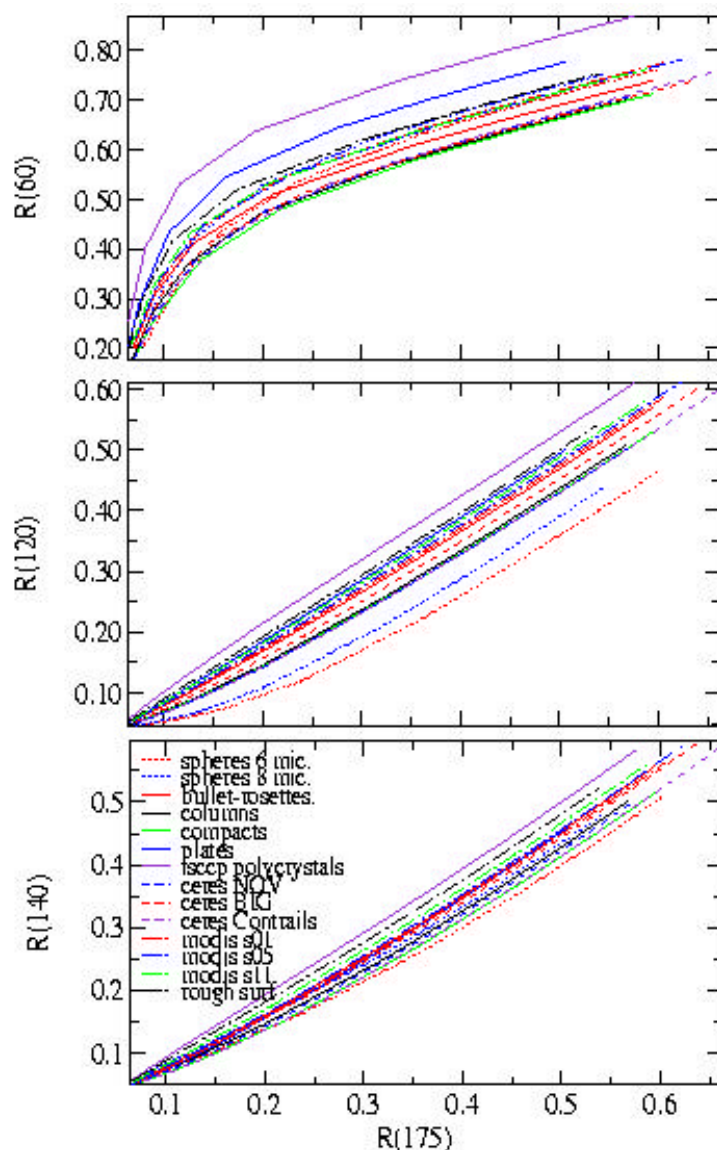


Figure 5. Theoretical variation of $0.65\text{-}\mu\text{m}$ reflectance relative to reflectance at a scattering angle of 175° for various ice crystal model shapes at scattering angles of 60° (top), 120° (middle), and 140° (bottom) for solar zenith angle of 40° over ocean surface from Chepfer et al. (2000b).

scattering albedo, and extinction efficiency (e.g., Yang et al. 1997), cloud particle shape affects the angular reflectance pattern from clouds and alters the relationship between optical depth and reflectance (e.g., Minnis et al. 1993). Cirrus and other ice clouds (e.g., cumulonimbus anvils) can be composed of particles having a variety of different shapes like hexagonal columns and plates, aggregates, bullet rosettes, and dendrites that may include trapped air bubbles or have rough surfaces. Each of these shapes can produce significantly different reflectance patterns for a given optical depth (e.g., Mishchenko et al. 1996, Mitchell et al. 1996, Chepfer et al. 2000a, Doutriaux-Boucher et al. 2000). Methods have not been developed for selecting the correct particle shape from a single-view, non-polarized imager like MODIS or VIRS. Thus, cloud monitoring by CERES or MODIS must assume one or more ice crystal shapes to model the relationships between reflectance, emittance, optical depth, and particle size (e.g. Minnis et al. 1998).

Errors due to the assumed shape may be determined by multi-angle observations (e.g., Minnis et al. 1993, Baran et al. 2000, Chepfer et al. 2000b). Figure 5 illustrates the potential for validating the reflectance models (i.e., crystal shape) from multiangle views by comparing the reflectances computed for two different viewing conditions for a fixed solar zenith angle over a range of optical depths for a variety of realistic particle shapes or distributions of shapes. The relationships between the two reflectances vary with scattering angle and show distinct differences between the various particle shapes. The degree of separation between the model reflectance curves changes with solar zenith angle and scattering angle pairs. To use such an approach for validating or determining the error due to the assumed CERES particle shapes (hexagonal columns), it will be necessary to determine theoretically the optimal angular combinations for distinguishing particle shape.

The assumption that clouds are plane-parallel infinite sheets that fill each pixel in the CERES retrieval models will introduce additional errors because of three-dimensional structure of real clouds, the finite size of clouds, and the misalignment between cloud and pixel boundaries. Theoretical studies examining the effects of cloud structure and partially filled pixels should continue to aid the validation and understanding of the retrieved properties in broken, mixed, and vertically inhomogeneous cloud fields.

4.3.3.2 Operational Networks

Various cloud properties are or will be regularly observed with active and passive surface systems at the University of Utah, Penn State University (PSU), University of Miami, and NASA Langley's Chesapeake Lighthouse as well as at several locations in Europe. Cloud optical depth and, possibly, cloud effective particle size can be derived from Multifilter Rotating Shadowband Radiometer (MFRSR) data (e.g., Min and Harrison 1996). These instruments have been deployed and operate continuously in networks over the United States and individually in several other countries including Australia, Bermuda, Taiwan, and Switzerland.

4.3.3.3 Existing Satellite Data

An enormous, growing archive of satellite data is available for both consistency studies and intercomparisons with field data. In addition to the relatively expensive, commercial and government archives of Landsat, AVHRR, GOES, SSM/I, GMS, and Meteosat, there are new, potentially less expensive sources such as the Pathfinder project and the various NASA DAACs. The ISCCP also maintains an archive of sampled AVHRR and geostationary satellite data. These data plus those from other satellites such as the ERS series, ADEOS-I, and RADARSAT would be useful for addressing some of the COPRS validation needs.

4.3.4 ADDITIONAL POST-LAUNCH ACTIVITIES

4.3.4.1 Planned field activities and studies

Subsets of the operational COPRS products will be compared to field data similar to those used during the prelaunch and initial post-launch studies. At this time, field experiments scheduled for 2001 and later include CRYSTAL and ARM/TWP IOPs in the Tropics, CLAMS over mid-latitude ocean, ARM/SGP IOPs over midlatitude land, and ARM/NSA IOPs in the Arctic. The NOAA Pan American Climate Studies (PACS) Program is planning a field experiment to study marine stratocumulus in the southeastern Pacific. Cloud microphysical and optical property measurements would be extremely valuable for validating CERES cloud retrievals in this domain which includes one of the CERES Cloud Validation regions (e.g., Figure 1). Special efforts should be made to obtain relevant datasets from that and other programs of opportunity and to develop some special CERES validation aircraft flights. The theoretical studies discussed earlier are ongoing and will continue during the post-launch phase.

4.3.4.2 New EOS-targeted coordinated field campaigns

Prelaunch activities plus the scheduled post-launch programs will not meet the COPRS needs. For example, there is an insufficient number of nocturnal, mountain, polar, and ocean, and desert cloud studies. The microphysical properties of clouds deriving from intense deep convection such as that over the Amazon Basin or over the midlatitude continents during Spring have not been examined in situ or with active remote sensors. Background characteristics are critical elements in the retrieval process, especially for optically thin clouds. The backgrounds near coasts and over deserts and mountains are extremely variable. Furthermore, the processes driving cloud formation in these areas may be different than those for simple convection, frontal storms, and marine stratocumulus. Thus, in addition to sponsoring new campaigns for developing validation sets over the larger climate systems, EOS should target some of the more difficult situations such as those that occur over mountains, deserts, and coasts. During all of the field experiments, more effort should be devoted to taking measurements at night and in situ data for multilayered clouds.

4.3.4.3 Needs for other satellite data

Multiple satellite studies should continue and be expanded during the CERES period to provide an assessment of relative errors and angular sensitivity of the optical properties derived from MODIS and VIRS. Data from the GOES imagers, AVHRR, and the Meteosat Second Generation SEVIRI, especially, will be extremely valuable for providing retrievals that are consistent with CERES but from different angles. The SSM/I and TRMM TMI should be used to derive independent estimates of *WP* over water surfaces to evaluate the COPRS results and to determine the contribution of liquid *WP* to total *WP* in thick ice-over-water cloud cases (e.g. Lin and Rossow 1996, Lin et al. 1998). Because it will be coincident with the VIRS data, the TMI will be especially valuable for direct continuous comparisons. Reflectance data from Triana will match all of the VIRS and MODIS data to within 30 minutes. Combined Triana and EOS imager data would be critical for evaluating the impact of the assumed scattering phase functions (particle shape) and of broken cloud effects on the CERES retrievals of optical depth and particle size because of the sensitivity of these effects to scattering angle. Data from ENVISAT, ADEOS-II (POLDER), and MISR (Terra) also be useful for similar COPRS validation efforts. While comparisons of some of these other satellite datasets will be conducted by the CERES Cloud Working Group, additional efforts are needed to ensure that validations using these other datasets are comprehensive.

4.3.4.4 Measurement needs at validation sites

The long-term and field program validation (e.g., ARM) sites should include microwave radiometers to determine liquid *WP*; sun photometers, and MFRSRs to derive optical depth; radars to determine cloud thickness, cloud microphysical properties, and vertical and horizontal structure; lidars to detect phase variations in clouds, cloud base heights, and optical depth for thinner clouds (item especially needed at night); infrared beam radiometers to estimate emittance; and radiosonde data to determine vertical humidity and temperature profiles.

In situ measurements should be taken periodically over the long-term sites to insure that the algorithms applied to the validation instruments are performing properly. Similar measurements of cloud particle size, phase, and shape, cloud water path, and optical depths should be performed intensively during the field campaigns.

4.3.4.5 Needs for instrument and algorithmic development

Because the number of long-term validation locations is so small, more sites are needed to represent

other climate regimes. To make the installation and maintenance of such sites possible, instrument development and algorithm automation should be pursued. For example, smaller, less expensive radars that draw less power would be critical to such efforts. Similar advances in the other instruments would also be welcome. Development of advanced algorithms is needed to derive accurate cloud microphysical properties from multilayer, multiphase, or broken cloud fields. Techniques incorporating radars and MFRSR oxygen A-band radiances (e.g., Min et al. 2000), or other instrument combinations should be refined and tested with in situ data and then implemented operationally where the instruments are available. Methods and/or instruments for accurately determining ice WP and D in optically thick ice clouds should be pursued because current measurement systems are inadequate or obtaining accurate values of those quantities. In situ measurements are also difficult because of the great vertical extent of thick ice clouds and the environment is often hazardous. Methods employing far-infrared technology (e.g., Evans et al. 1998) show some promise for accomplishing this elusive measurement.

The logistical problems involved in deploying instrument suites in remote areas such as deserts, mountains, or on ocean buoys should also be considered in the development of new instrumentation. Current sites that lack a full complement of instruments should be encouraged to obtain them and make them operational. Other institutions that have some of the necessary hardware should be called upon to deploy their instruments and analyze their datasets.

4.3.4.6 Intercomparisons

The COPRS can produce different values for the same cloud properties because of multiple algorithms in the subsystem. Thus, one of the first -order intercomparisons should be between the various COPRS results. Why they differ and when should be understood as well as possible. When both the TRMM and AM-1 are operating together, the COPRS results from both satellites should be compared whenever the satellites cross. MODIS and COPRS datasets should also be examined together for the same purpose. The COPRS datasets should also be compared to WP derived from the SSM/I and TRMM data as noted earlier. Other comparisons between in situ, ground and aircraft sensors, and other satellites should be performed as discussed earlier.

4.3.5 VALIDATION RESULTS IN DATA PRODUCTION

4.3.5.1 Approach

The validation of cloud properties will take place at the CERES SCF and at the outside investigators' home institutions. While some of the global mapping functionality can be automated, most of the effort described in this document requires interaction with an investigator. The investigator will need ready access to cloud boundary information from each of the ARM sites or other sites that are operationally providing cloud boundary information, as well as access to the subsetted data sets of retrieved cloud properties.

4.3.5.2 Role of EOSDIS

The EOSDIS should facilitate access to the required satellite and validation site datasets. In that capacity, it may serve as a repository or connection for relevant field program data. Current NASA DAACs are already filling this role to a certain degree. The acquisition of non-operational and other EOS satellite data should be undertaken by EOSDIS or the NASA Langley DAAC to minimize redundancy and amplify the utility of the correlative satellite datasets.

4.3.5.3 Plans for Archival of Validation Data

The retrieved cloud parameters listed in Table 4.4-4 of CERES Subsystem 4.4, entitled "Convolution of imager cloud properties with CERES footprint point spread function", the volume of one hour of pro-

cessed imager data is approximately 600 MB. These retrievals are not a product, but are subsequently convolved with CERES footprints to give a combined radiation-cloud-property product. The swaths (e.g., Figure 1) including the cloud validation regions (see Table 2 of Minnis et al. 2000) and 351 1° x 1° CERES (all working groups) validation regions constitute the only pixel-level cloud parameter data saved by CERES. These validation datasets are produced and archived by the Langley DAAC.

The EOSDIS DAACs should continue to archive the field program data and expand its connection to other archives of relevant data. For example, there should be links between the EOSDIS and ARM archives to smooth the acquisition of the necessary validation sites. Other validation site operators should be encouraged to submit their datasets to the EOSDIS for more widespread use. Combined CERES-outside validation datasets used by the CERES Science Team or validation collaborators should be archived by the DAAC after the initial studies are completed.

4.3.6 SUMMARY

The CERES COPRS validation plan is an ambitious effort directed at the determination of the uncertainties in the cloud microphysical properties derived from the VIRS and MODIS imagers. It requires both theoretical and empirical studies that will employ large quantities of satellite data, a variety of field programs, long-term monitoring sites, and numerous modeling studies. The remote sensing of cloud properties is a relatively new science examining a very complex system. Necessarily, the validation of the derived products is an involved task. Success in this effort will be determined by convergence of the uncertainty estimates. Thus, expanding the statistical representation of the correlative data is essential. The approach builds from the small-scale in situ data to larger time scales based on continuous measurements at the surface. Intercomparisons of the surface and satellite retrievals provides a measure of the absolute errors in the products. Comparisons of multiple satellite retrievals over large areas at various angles establishes a large statistical database that will provide angle and scene-dependent estimates of relative errors as well as precision of the results. Theoretical calculations lead to error estimates arising from the various physical constraints on the retrieval system. These modeling approaches can be used to better understand the errors and to search for methods to minimize them. Together, the theoretical and empirical analyses should provide a quantitative estimate of each COPRS product for a variety of conditions.

This effort calls for the development of additional programs to measure cloud characteristics with aircraft and surface instruments in climate and surface-type regimes neglected in earlier studies. Expansion of long-term monitoring of cloud properties from surface sites is also requested. The COPRS validation datasets should combine CERES COPRS and correlative data in a scientific archive, preferably, EOSDIS or the Langley DAAC, to provide for more scientific analysis.

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4.3.8 LIST OF ACRONYMS

ACE	Atmospheric Chemistry Experiment
ADEOS	Advanced Earth Observing System
ARM	Atmospheric Radiation Measurement Program
ARMCAS	Arctic Radiation Measurements in Column Atmosphere-surface System
ASTEX	Atlantic Stratocumulus Transition Experiment
ATSR-2	Along-Track Scanning Radiometer
AVHAVHRR	Advanced Very High Resolution Radiometer
BOREAS	The Boreal Ecosystem-Atmosphere Study
CASP	Canadian Atlantic Storms Program
CEPEX	Central Equatorial Pacific Experiment
CERES	Clouds and the Earth's Radiant Energy System Project
COPRS	Cloud Optical Property Retrieval Subsystem
CLAMS	Chesapeake Lighthouse and Aircraft Measurements for Satellites
CRYSTAL	Cirrus Regional Study of Tropical Anvils and Cirrus Layers
DAAC	Distributed Active Archive Center
ENVISAT	Environmental Satellite
ERBE	Earth Radiation Budget Experiment
ERS	Earth Resources Satellite
EUCREX'94	European Cloud Radiation Experiment 1994
FASTEX	Fronts and Atlantic Storm Track Experiment
FIRE	First ISCCP Regional Experiment

FRIZZLE	Freezing Drizzle Experiment
GOES	Geostationary Operational Environmental Satellite
GMS	Geostationary Meteorological Satellite
ICE	International Cirrus Experiment
INDOEX	Indian Ocean Experiment
INCA	INterhemispheric differences in Cirrus properties from Anthropogenic emissions
IOP	Intensive Observing Period
ISCCP	International Satellite Cloud Climatology Project
MAS	MODIS Airborne Simulator
MAST	Monterrey Area Ship Tracks
MCTEX	Marine Continental Thunderstorm Experiment
MODIS	Moderate Resolution Imaging Spectrometer
MPIR	Multispectral Pushbroom Radiometer
NARE	North Atlantic Regional Experiment
NAURU99	Nauru Island ARM Experiment in 1999
NSA	North Slope of Alaska
PACS	Pan American Climate Studies
PSU	Pennsylvania State University
PSUCS	PSU Continental Stratus Experiment
RACE	Radiation, Aerosol, and Climate Experiment
SAFARI	South African Regional Science Initiative
SCAR	Smoke Clouds and Radiation Experiment
SGP	Southern Great Plains
SHEBA	Surface Heat Budget in the Arctic
SSM/I	Special Sensor Microwave/Imager
STERAO	Stratosphere Troposphere Experiments: Radiation, Aerosols, and Ozone
SUCCESS	Subsonic Cirrus and Contrails Special Study
TRMM	Tropical Rainfall Measurement Mission
UAV	Unmanned Aerospace Vehicle
VIRS	Visible and Infrared Scanner
WISP	Winter Icing Storms Project

CERES 1

VALIDATION OF IMAGER CLOUD OPTICAL PROPERTIES

DATA PRODUCTS

CLOUD *PHASE*, *EFFECTIVE PARTICLE SIZE*, *WATER PATH*, *OPTICAL DEPTH*, *EMITTANCE*, *RADIATING TEMPERATURE*, & *THICKNESS*

MISSIONS

TRMM, *EOS AM-1*, & *EOS PM-1*

APPROACH: BOTH PRE- & POST-LAUNCH

- COMPARISONS WITH *IN SITU* & *SURFACE/AIRCRAFT REMOTE SENSING*

YIELDS ESTIMATE OF BIAS ERRORS

- SIMULTANEOUS RETRIEVALS FROM *MULTIPLE SATELLITES OR AIRCRAFT & SATELLITE*

PRODUCES STATISTICS, RELATIVE ERRORS, & SCENE/ANGLE DEPENDENCE

- MODEL CALCULATIONS TO *DETERMINE ALGORITHM SENSITIVITIES TO INPUT & ASSUMPTIONS*

LEADS TO PHYSICAL UNDERSTANDING OF OBSERVATIONS

CERES 2

VALIDATION OF IMAGER CLOUD OPTICAL PROPERTIES

PRELAUNCH

- COMPLETE ANALYSES OF FIELD PROGRAM DATA & COMPARE WITH SATELLITE RETRIEVALS
- DEVELOP & ANALYZE MATCHED SATELLITE DATASETS HAVING APPROPRIATE SPECTRAL CHANNELS
- STUDY ALGORITHM SENSITIVITY TO CLOUD INHOMOGENEITIES, VIEWING & ILLUMINATION CONDITIONS, BACKGROUND, & INPUT
- IDENTIFY KEY CLIMATE REGIMES NEEDING FURTHER VALIDATION

POST-LAUNCH

- INCREASE NUMBER OF LONG-TERM MONITORING SITES
- DEVELOP FIELD PROGRAMS & INSTRUMENTS FOR LONG-TERM DEPLOYMENT

- **PERFORM QUICK-LOOK ANALYSES OF GLOBAL PRODUCTS**
- **COMBINE FULL-RESOLUTION CERES AND VALIDATION SITE DATASETS, PERFORM COMPARISONS**
- **COMPARE RETRIEVALS TO THOSE FROM OTHER SATELLITES & INSTRUMENTS**

EOSDIS

- **FACILITATE DATASET ACQUISITION**
- **ARCHIVE COMBINED CERES & CORRELATIVE DATASETS**